



## Monsoon indicators for Borneo

Ramzah Dambul<sup>1</sup>

<sup>1</sup>School of Social Sciences, Universiti Malaysia Sabah, 88999 Kota Kinabalu, Sabah

Correspondence: Ramzah Damhul (email: [rymza@ums.edu.my](mailto:rymza@ums.edu.my); [rdambul@gmail.com](mailto:rdambul@gmail.com))

### Abstract

The two most significant synoptic forces governing the climate of the Southeast Asia region are the Asian Monsoon and El Niño Southern Oscillation (ENSO). Several previous studies had successfully established climatic indices to capture the signals of these two large-scale circulations. Such indices would enable researchers to investigate empirical relationships between synoptic forces and the local climate of a particular region. However, the monsoon indices created from these previous studies were based on the geographical layout over much larger areas, which covered the south and east Asian regions. In order to better understand the influences of monsoon signals on the local climate of Borneo, RD1 and RD2 monsoon indices are, therefore, established. These new indices are created using sea-level pressure within the specific domain of Southeast Asia, which is 75° E – 140° E; 20° S – 30° N. They are created specifically to diagnose relationships between monsoon signals and the surface climate of Borneo, and to suit the local features of the region.

**Keywords:** Borneo, El Niño Southern Oscillation (ENSO), local climate, Monsoon indices, surface climate, synoptic forces

### Introduction

There are two major features of the large-scale circulation in Southeast Asia, namely the low-frequency ENSO signals (2-7 years) and the seasonal monsoon modes fluctuating within the annual cycle. The main centre of action for the monsoon is the South China Sea within the area 2.5°-22.5°N and 102.5°E-122.5°E (Lu and Chan, 1999). However, the energy sources to stimulate the monsoonal flows originate from the mainland of the Asian continent (to the north), Indian Ocean (to the west), the Australian continent (to the south) and the western equatorial Pacific (to the east). ENSO, on the other hand, is a synoptic forcing that originates from the middle of the Pacific Ocean.

- Monsoon and ENSO are the most influential forces modulating surface climate in many parts of the world (Nieuwolt, 1977; Allan et al., 1996) – thus, many studies have been conducted to develop indices for both of these large-scale factors (e.g. Ropelewski and Jones, 1987; Barnston and Chelliah, 1997; Goswami et. al, 1999). The main purpose for such indices is to enable researchers to investigate empirical relationships between these two synoptic phenomena and the local climate of a particular region.
- In Borneo's case, these two forces (i.e. the monsoon and ENSO) form and modulate the local climate (Sham Sani, 1984; Sirabaha, 1998). Therefore, in order to understand the local climate of Borneo, it is crucial to investigate how these two synoptic forces act and interact to, eventually, form the large-scale circulation over the Southeast Asian region.

### *Monsoon*

For the south Asian monsoon (also known as the Indian monsoon), which generally emphasizes summer rainfall, Lu and Chan (1999) identify two indices that have the ability to detect strong and weak monsoonal events. The first one is the all-Indian rainfall index (AIRI), which uses the

precipitation average for June-September in subcontinental India (Krishnamurti, 1971). The other one is known as the WY index. It is represented by the zonal wind shear between 850 and 200 hPa over Southeast Asia (Webster and Yang, 1992). Both of these indices have been further improved by later works of other researchers (Parthasarathy et al., 1995); Goswami et al., 1999; and Wang and Fan, 1999).

According to Lu and Chan (1999), the situation is more complicated in the case of the east and southeast Asia monsoon, which consists of three major airflows i.e. (1) southwesterly flow (part of the Indian monsoon), (2) southeasterly flow (from the southwestern edge of the western Pacific sub-tropical high), and (3) the cross-equatorial flow over the southern part of the South China Sea (adjacent to Borneo). Whilst the summer monsoon is more dominant in the south Asia region (in terms of surface climate teleconnections – i.e. precipitation), the winter monsoon is stronger in the east and southeast Asia region (Lu and Chan, 1999; Lau et al., 2000). The monsoon in this region also shows a very distinctive wind component, which is southerly (northerly) during the boreal summer (winter).

Some of the most well-known and widely accepted monsoon indices are listed in Appendix A. There are three issues worth to be considered if these readily-established indices are being applied to Borneo:

- Most of the indices are specifically developed for either the south or east Asian regions. Ideally, as been pointed out by Wang and Fan (1999), any Asian monsoon index should be associated with the broad-scale flow of the Asian monsoon regions (this includes the Indian continent, Southeast Asia – both the mainland and the maritime continent, and East Asia). However, some researchers (e.g. Tao and Chen, 1987; Ding, 1994) argue that local manifestations can be significantly varied when the monsoon components move across different latitudes, land-sea contrast and topography. Thus, it is totally sensible to assume that these indices may not fit well to Borneo.
- Most of the indices focus on the summer monsoon and they are based on the larger monsoon region (it normally includes both the southern and eastern part of Asia). According to Wu and Chan (1997), while the winter monsoon may be adequately represented by the planetary-scale flow, this may be questionable for the summer monsoon. It is evident that Borneo experiences equally noticeable effects during the winter and summer monsoon (Sham Sani, 1984). Therefore, a more local approach is required to find the best monsoon indices to diagnose the local climate of Borneo.
- All the existing indices are seasonal/annual measures except for the Unified Monsoon Indices by Lu and Chan (1999), which are calculated on a monthly basis for both monsoons. Therefore in most cases, correlation analysis could not be performed on monthly or daily values. Thus, this will limit the investigation of the monsoon influences on precipitation/temperature on these time scales.

### ENSO

ENSO indices are generally represented by two climatic variables – (a) the sea level pressure; and (b) sea surface temperature (SST). The well-established specific indices are listed in Table 1.

**Table 1. Established ENSO indices**

Index	Climatic Variables	Description	Timescale
SOI	Sea level pressure (SLP)	SLP difference between Tahiti/Darwin	Monthly
Niño 1+2	Sea surface temperature (SST)	SST anomaly at the Niño-1 + 2 region	Monthly
Niño 3	Sea surface temperature (SST)	SST anomaly at the Niño-3 region	Monthly
Niño 3.4	Sea surface temperature (SST)	SST anomaly at the Niño-3.4 region	Monthly
Niño 4	Sea surface temperature (SST)	SST anomaly at the Niño-4 region	Monthly

Based on the published literature, a consensus is clearly exhibited on what are the most suitable ENSO indices for Southeast Asia. Most of the previous studies (Quah, 1988; Cheang, 1993; Tangang, 2001; Caesar, 2002; Sirabaha, 2004) have opted for SOI (Southern Oscillation Index) and Niño-3.4 (SST anomaly for the Niño-3.4 region) as the best indices to be associated with surface climate of Southeast Asia.

## Evaluation of established monsoon indices

The method used to evaluate the monsoon indices is a simple non-parametric correlation. These indices are correlated with surface variables of Borneo (i.e. precipitation and temperature), and the well-established ENSO indices. There are two underlying characteristics of the monsoon phenomenon:

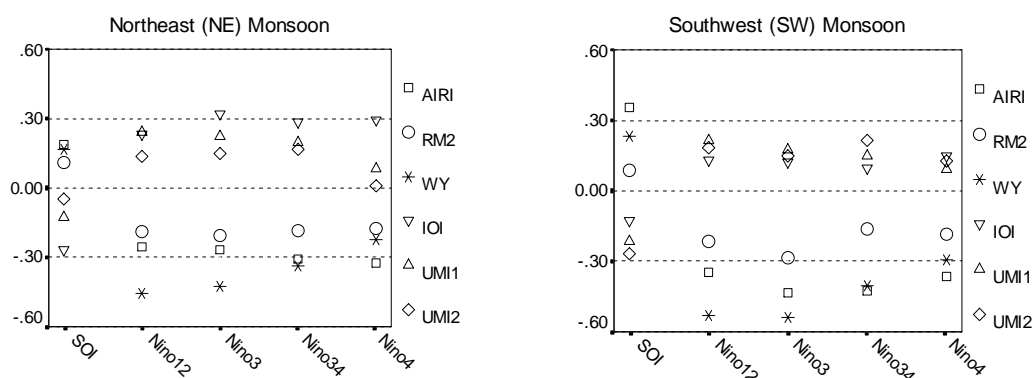
- The monsoon modulates the climate of Borneo on a seasonal basis (fluctuating within the 12-month annual cycle).
- The monsoon interacts with the ENSO signal, which is responsible for the incidence of El Niño or La Niña events.

Using this prior knowledge, two criteria are identified to measure and justify the suitability of the monsoon indices – prior to the correlation analysis. The criteria are:

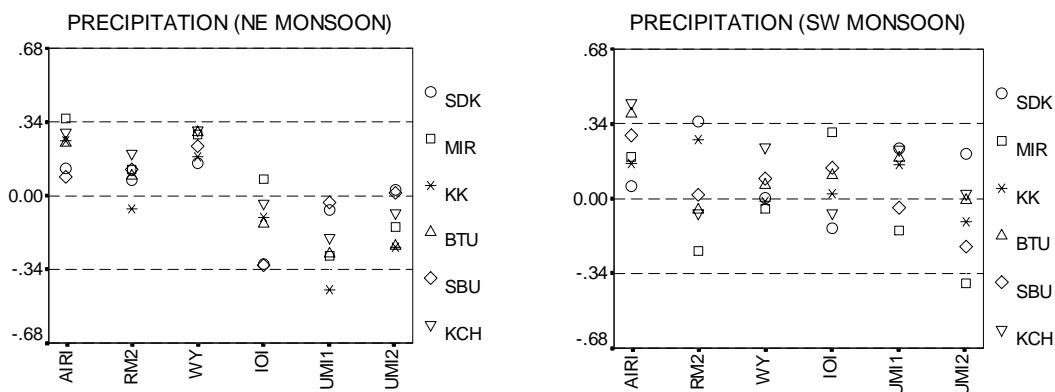
- The correlation between the monsoon indices and the surface variables (precipitation and temperature) must be convincing in both seasons (winter and summer monsoon). This could indicate that the indices have the ability to capture the seasonal variability.
- The correlation between the monsoon indices and ENSO indices (especially SOI and Niño3.4) must be highly significant. These measure the ability of the monsoon indices to phase-lock with the ENSO signals (the most prominent variability on multiyear timescales).

The results of the correlation analysis are shown in Figures 1-3. The thresholds of correlation coefficient values at 95% level of significance are 0.30 (for Monsoon-ENSO) and 0.34 (for Monsoon-Surface). The differences in threshold are due to the length of the data series: 42 years (1960-2001) for the monsoon and ENSO indices; and only 34 years (1968-2001) for precipitation and temperatures.

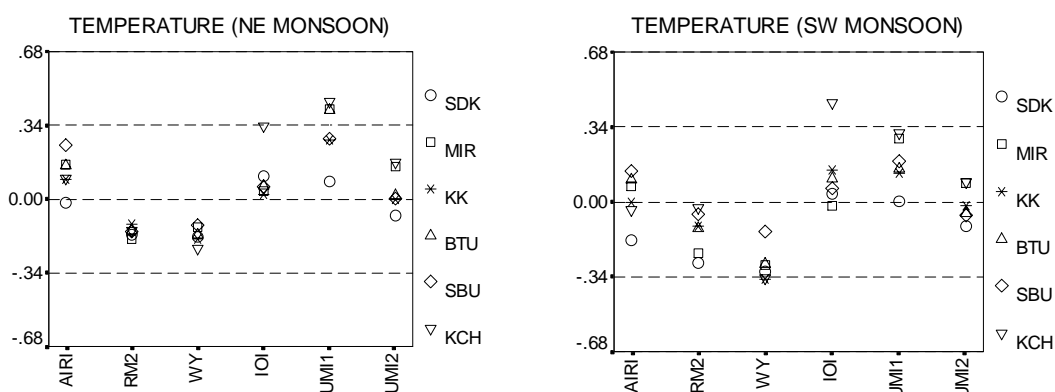
The evaluated monsoon indices are AIRI, RM2, WY, UMI1, UMI2 (see Table 1), and IOI (Indian Ocean Index), represented by the mean SST over Indian Ocean region bounded by 20° N–10° S and 50° E–100° E and computed in a 5° X 5° grid using the ship's observations archived by the National Data Centre of the India Meteorological Department. AIRI and WY are only available for the summer (SW) monsoon. Therefore, the correlation values for AIRI and WY during the winter (NE) monsoon are based on the seasonal values for the SW monsoon (i.e. with six month lag).



**Figure 1.** Correlation between selected monsoon indices (from previous studies) and well-established ENSO indices for two different monsoons



**Figure 2.** Correlation between selected monsoon indices (from previous studies) and precipitation at 6 key stations in Borneo for two different monsoons



**Figure 3.** Correlation between selected monsoon indices (from previous studies) and temperature anomaly at 6 key stations in Borneo for two different monsoons

ENSO indices are SOI, Niño1+2, Niño3, Niño3.4 and Niño4 (see Table 1). Particular attention is given to SOI and Niño3.4, the two indices which are considerably the most representative of Borneo. Six key stations in Borneo are SDK (Sandakan), MIR (Miri), KK (Kota Kinabalu), BTU (Bintulu), SBU (Sibu) and KCH (Kuching). In general, the chosen monsoon and ENSO indices are poorly correlated. During the winter (Northeast) monsoon, none of the indices is significantly correlated with SOI, and only WY (0.36) is statistically significant during the summer (Southwest) monsoon. As for the Niño3.4, only AIRI (-0.31/-0.43) and WY (-0.34/-0.40) are significantly correlated in both seasons (winter/summer). All the other indices are statistically not significant.

The correlation with the surface climate of Borneo is also relatively poor. Only UMI1 shows significant correlation with more than one station (MIR, BTU, KCH) for temperature during the winter (Northeast) monsoon. The other indices have a maximum of only two stations significantly correlated with either temperature or precipitation. However, none of the indices prove to be reliable for both surface variables (i.e. precipitation average and temperature anomaly) in both seasons (summer and winter).

## Methodology and results

### *Creating and evaluating the new monsoon indices*

Upon evaluating several established monsoon indices used by previous studies (mostly using zonal and meridional upper wind shear at various hPa levels), none of these indices establish convincing correlation with either the surface climate or the ENSO signals. In particular, most of the indices fail to establish reasonable teleconnections during the boreal winter i.e. the season that

supposedly manifests stronger monsoon effect for Southeast Asia (as has been reviewed by Sham Sani, 1984; Sirabaha, 1998; 2004). Therefore, it is appropriate, indeed essential, to create new indices using a more 'local approach'.

In establishing the new synoptic climate indicators (to capture monsoon signal), the chosen centre is the domain covering 20°S-30°N; 75°E-140°E. What is the justification for this new choice of so-called 'action centre'? The main domain of action for the Southeast Asia Monsoon (SEAM) is between northern Australia and mainland Asia. Although there are various physical mechanisms that force the movement of the SEAM flow, the main source is the meridional thermal contrast between the northern and southern hemispheres (Lu and Chan, 1999). Since Borneo is located right on the equatorial line, the 20°S-30°N latitudinal ranges is appropriate.

The synoptic variable used to create the new indices is sea level pressure (SLP). Most of the previous indices are based on upper level wind (at 1000, 850 and 250 hPa). This might be an appropriate approach to establish indices for the broader-scale monsoon region (i.e. the entire continent of South Asia or Far East Asia). However, for a smaller region like Borneo, the lower level wind is considered more effective (Sirabaha, 1998). There are two reasons why SLP is a better choice – (i) to introduce a fresh perspective in the search of monsoon indices (i.e. in the pervious studies, there is no attempt to establish monsoon index based on sea level pressure); and (ii) SLP, the lower level wind, has two advantages – which is the ability to reflect the large-scale signal, and (equally) to capture the more local influences of geographical layout and land-sea distribution.

The SLP is derived from the gridded reanalysis data for the chosen window (20°S-30°N; 75°E-140°E – regarded as the monsoon action centre for Southeast Asia). Daily observations from 1960-2001 (42 years) with the grid resolution of 2.5° X 2.5° are used. The two specially created monsoon indices are named RD1 and RD2.

#### *The first new index (RD1): SLP differences*

Similar to the basic principle in creating the SOI, RD1 is a simple index using pressure differences between two identified points/areas. The two points are (a) the northern latitude of 30°N; and (b) the southern latitude of 20°S. These are the starting latitudinal lines where the low-level wind changes its direction during the seasonal transition between winter and summer, and vice versa (Sham Sani, 1984).

The daily values of RD1 are obtained from the differences between the averages of SLP values along the two latitudinal lines – 30°N and 20°S (27 grid-points of 2.5° X 2.5° in each line between the longitudes 75°E-140°E). The index can be mathematically represented by this equation:

$$\text{RD1 Index} = \text{AVG}(\text{SLP}_{30^{\circ}\text{N}})_{n=1,27} - \text{AVG}(\text{SLP}_{20^{\circ}\text{S}})_{n=1,27}$$

Where,

SLP<sub>30°N</sub> is the averaged SLP values for 27 grid-points along the 30°N (latitude line)

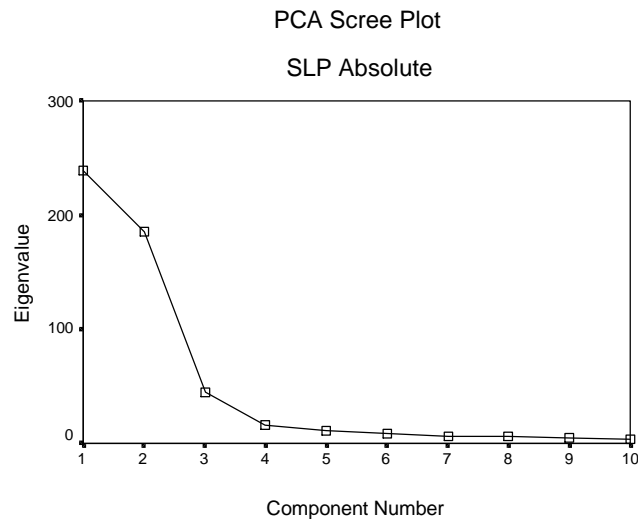
SLP<sub>20°S</sub> is the averaged SLP values for 27 grid-points along the 20°S (latitude line)

#### *The second new index (RD2): unrotated PC modes*

This second index is more complex. RD2 values are obtained from the unrotated PC scores – the product of Principal Component Analysis (PCA), which is operated on the absolute measure of daily SLP (1960-2001). The basic assumption applied here is that the daily SLP gridded values at 567 grid points (which are evenly distributed over the chosen window) – could collectively represent the monsoon mode.

However, there would be an issue of having too many values to serve as diagnostic indices. Thus, PCA aims to reduce these variables and produce fewer significant modes, which should simplify the temporal variability. There are three important processes in achieving this, by using PCA:

- To reduce the 567 grid-point variables into fewer significant modes
- To combine the identified significant modes into one single monsoon index
- To calculate values to represent each day over the time series (these daily observations can be converted into monthly, seasonally or annual values – depending on the need)



**Figure 4.** Scree Plot of the PCA

The core objectives neither include regionalisation nor map-pattern classification. Therefore, the most appropriate mode of decomposition is the P-mode (Yarnal, 1993). In this case, the PCA serves purely as a reduction process. There are four significant components, which cumulatively describe a total variance of 86% (see Table 2). The scree plot used as the main criterion to identify the significant modes (Cattell, 1966 and Preisendorfer, 1988). The optimum number of PCs that should be retained is determined by the point where the eigenvalue's plot start bending (i.e. it is the component number 4 – see Figure 4).

**Table 2. Percentage of variance explained by each PCA**

Retained PC	Unrotated Eigenvalues		
	Total	% of Variance	% Cumulative
PC 1	239	42	42
PC 2	185	33	75
PC 3	45	8	83
PC 4	17	3	86

Each one of the retained components could, itself, serve as a monsoon index. However, the four components theoretically represent various physical features of the monsoon signals. Therefore, each one of them can only capture a certain fraction of the total variability in the monsoonal flow. In order to obtain the more holistic and representative index, the calculation of the final value is done by averaging the score of all four retained components – and each component is weighted by its individual percentage of variance explained. The calculation is shown by the mathematical equation below:

$$RD2 \text{ Index} = [(PC1 \bullet V\%1) + (PC2 \bullet V\%2) + (PC3 \bullet V\%3) + (PC4 \bullet V\%4)] / 4$$

Where;

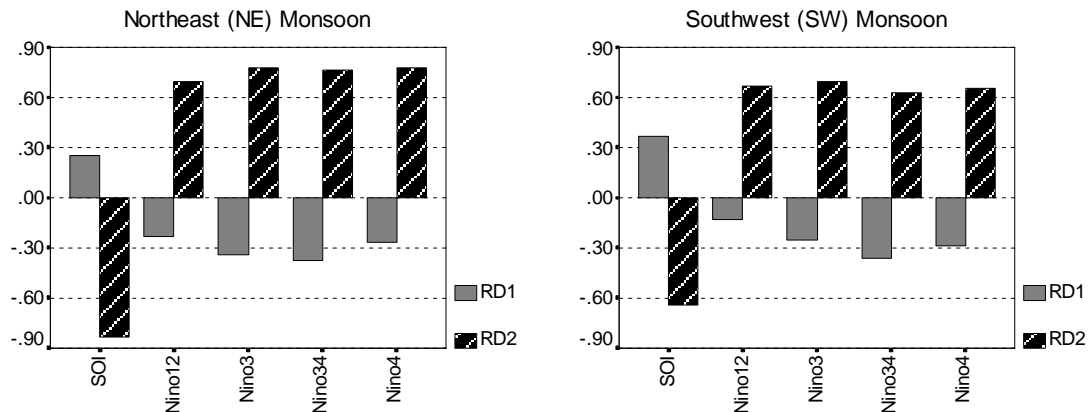
PC is the component score of PC1, PC2, PC3 and PC4

V% is the percentage of variance explained by PC1, PC2, PC3 and PC4 (see Table 3)

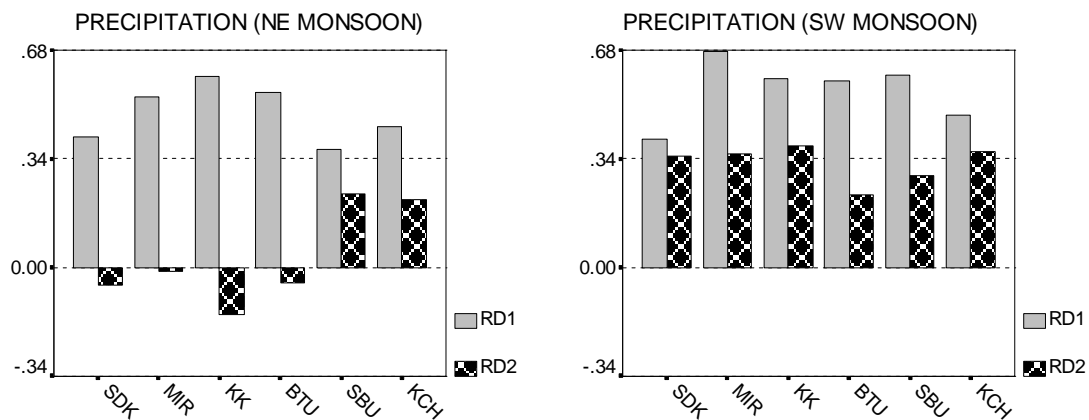
#### *Evaluation of the new monsoon indices (RD1 and RD2)*

These new RD1 and RD2 indices will be correlated with two other climatic variables – namely the ENSO indices and the local climate parameters (precipitation and temperature). These correlations are shown in Figure 5 (0.30 is the threshold for statistical significance at the 95% level). The correlations between surface climate parameters (precipitation average and temperature anomaly) are shown in Figures 6 and 7 respectively (0.34 is the threshold for statistical significance at the 95% level).

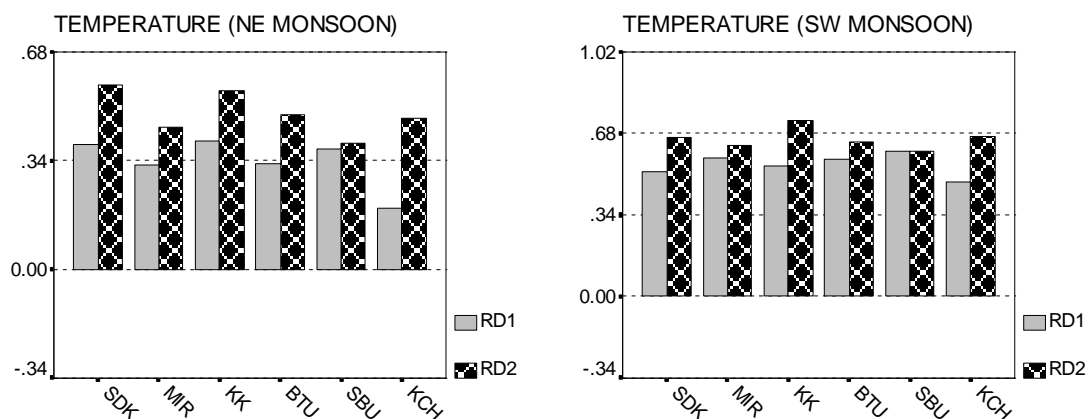
In comparison with the previously established indices (Figures 1 to 3), the results clearly indicate that these two new indices (RD1 and RD2) show better correlation with both types of variables – i.e. the local climate and ENSO indices. Based on this overall performance, it is clear that even the strongest index from the previous indices (i.e. WY) is weaker than the weakest of the newly created indices (i.e. RD1).



**Figure 5.** Correlation between RD1/RD2 and ENSO indices



**Figure 6.** Correlation between RD1/RD2 indices and Borneo seasonal precipitation



**Figure 7.** Correlation between RD1/RD2 indices and Borneo seasonal temperature anomaly

Of the two indices, RD1 is more strongly correlated with precipitation; whereas RD2 does perform better with temperature anomaly and the ENSO indices. Both indices show much better association during the winter (NE) monsoon, as opposed to the previous indices – which are clearly biased to the summer (SW) monsoon. The results for RD1 and RD2 are summarised in

Tables 3 and 4. The highest correlation between ENSO indices and the old monsoon indices (during the NE Monsoon) are: SOI – IOI (-0.27), Niño12 – WY (-0.46), Niño3 – WY (-0.42), Niño3.4 – WY (-0.34) and Niño4 – AIRI (-0.33). The highest correlation during the SW Monsoon are: SOI – AIRI (0.36), Niño12 – WY (-0.53), Niño3 – WY (-0.54), Niño3.4 – AIRI (-0.43) and Niño4 – AIRI (-0.36). RD2 proves to perform better than any of these monsoon indices created from previous studies.

**Table 3. Correlation values for RD1/RD2 during the winter (NE) monsoon**

3a Correlation coefficients with ENSO indices

	SOI	NIÑO12	NIÑO3	NIÑO34	NIÑO4
RD1	0.24	-0.23	-0.34*	-0.38*	-0.26
RD2	-0.84*	0.70*	0.78*	0.77*	0.78*

3b Correlation coefficients with precipitation

	SDK	MIR	KK	BTU	SBU	KCH
RD1	0.41*	0.53*	0.60*	0.55*	0.37*	0.44*
RD2	-0.05	-0.01	-0.15	-0.05	0.23	0.21

3c Correlation coefficients with temperature anomalies

	SDK	MIR	KK	BTU	SBU	KCH
RD1	0.39*	0.33	0.40*	0.33	0.38*	0.19
RD2	0.58*	0.45*	0.56*	0.49*	0.40*	0.47*

*Values marked with (\*) are statistically significant, at least, at the 95% level*

**Table 4. Correlation values for RD1/RD2 during the summer (SW) monsoon**

4a Correlation coefficients with ENSO indices

	SOI	NIÑO12	NIÑO3	NIÑO34	NIÑO4
RD1	0.37*	-0.13	-0.25	-0.36*	-0.29
RD2	-0.64*	0.67*	0.70*	0.63*	0.66*

4b Correlation coefficients with precipitation

	SDK	MIR	KK	BTU	SBU	KCH
RD1	0.40*	0.68*	0.59*	0.58*	0.60*	0.48*
RD2	0.35*	0.35*	0.38*	0.23	0.29	0.36*

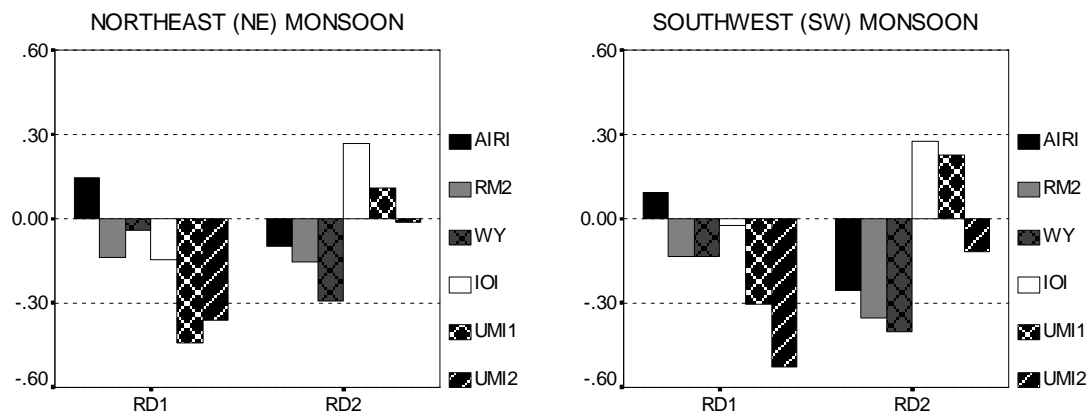
4c Correlation coefficients with temperature anomalies

	SDK	MIR	KK	BTU	SBU	KCH
RD1	0.52*	0.58*	0.54*	0.57*	0.61*	0.48*
RD2	0.66*	0.63*	0.73*	0.64*	0.61*	0.67*

*Values marked with (\*) are statistically significant, at least, at the 95% level*

These new indices (RD1 and RD2) are also correlated fairly well with some of the previous monsoon indices, particularly the UMI1 and RM2 indices – as shown in Figure 8 (0.30 is the threshold for statistical significance at the 95% level).





**Figure 8.** Correlation between RD1/RD2 and other monsoon indices

## Conclusion

Two newly-created monsoon indices are introduced (RD1 and RD2) to diagnose relationships between monsoon signal and the surface climate of Borneo. They are created specifically to suit the local features of the region. The advantages of using these new indices are:

- i) the indices are developed using lower level circulation (SLP) which translates better the physical and geographical layout of Borneo, instead of the upper level winds at geopotential heights of 200mb, 850mb and 1000mb (Refer to Appendix A);
- ii) the indices are calculated on a daily timescale, which makes them more flexible to be transformed into monthly or seasonal measures – depending on the purposes and aims of a particular study;
- iii) the indices are statistically proven to have stronger correlations with both the ENSO indices and local climatic variables (i.e. precipitation magnitude and temperature anomaly);
- iv) the indices exhibit reasonable correlations with other established monsoon indices – suggesting that the method used to develop these new indices has been created under a good theoretical foundation (i.e. consistent with previous studies).

**Appendix A**  
**List of well-established monsoon indices**

Author	Index	Climatic variables used to establish indices	Monsoon region	Time-scale & Season
Webster and Yang (1992)	Webster and Yang Monsoon Index (WYI**)	The time-mean zonal wind (U) shear between 850 and 200 hPa (U850 – U200); averaged over south Asia from the equator to 20°N, and from 40°E to 110°E	Large-scale Asian monsoon region and South Asia region (excluding northern Bay of Bengal and a portion of south China)	Seasonal values for Summer Monsoon
Parthasarathy et al. (1995)	All Indian Rainfall Index (AIRI**)	Seasonally averaged rainfall over all Indian sub-divisions from June-September (1871 – 1995)	South Asia region (excluding northern Bay of Bengal and a portion of south China)	Seasonal values for Summer Monsoon
Goswami et al. (1999)	Monsoon Hadley Circulation index (MH)	The time-mean meridional wind (V) difference between 850 and 200 hPa (V850 – V200); averaged over the region of 10°N-30°N and 70°E-110°E	South Asia region (including northern Bay of Bengal and a portion of south China)	Seasonal values for Summer Monsoon
Wang and Fan (1999)	Convection Index (CI1 and CI2)  Difference in Zonal (U) Wind (DU2)	CI1: negative outgoing longwave radiation (OLR) anomalies over the region of 10°N-25°N and 70°E-100°E  CI1: negative OLR anomalies over the region of 10°N-25°N and 115°E-140°E  DU2: meridional (U) wind difference at 850 hPa between region 5°-15°N; 90°E-130°E and region 22.5°-32.5°N; 110°E-140°E	CI1 for south Asian summer; CI2 and DU2 for southeast Asian summer monsoon	Seasonal values for Summer Monsoon
Lu and Chan (1999)	Unified Monsoon Index (UMI1**, UMI2**, UMI3)	UMI1: difference between meridional wind at 1000 hPa and 200 hPa (V1000 – V200)  UMI2: the monthly average of meridional wind component at 1000 hPa  UMI3: monthly average of meridional wind component at 200 hPa  All calculations are over the region of South China Sea (2.5°-22.5°N; 102.5°E-122.5°E)	UMI1, UMI2 and UMI3 mainly for East Asia region	Monthly values for both monsoons (summer and winter)
Lau et al. (2000)	Regional Monsoon Index (RMI1 and RMI2**)	RMI1: the time-mean meridional wind (V) difference between 850 and 200 hPa (V850 – V200); averaged over the region of 10°N-30°N and 70°E-110°E  RMI2: the time-mean zonal wind (U) at 200 hPa between region 40°N-50°N; 110°E-150°E and region 25°N-32.5°N; 110°E-150°E	RM1 for South Asia region and RM2 for East and Southeast Asia region	Seasonal values for Summer Monsoon

*Indices marked with \*\* are chosen in the comparison analysis*

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